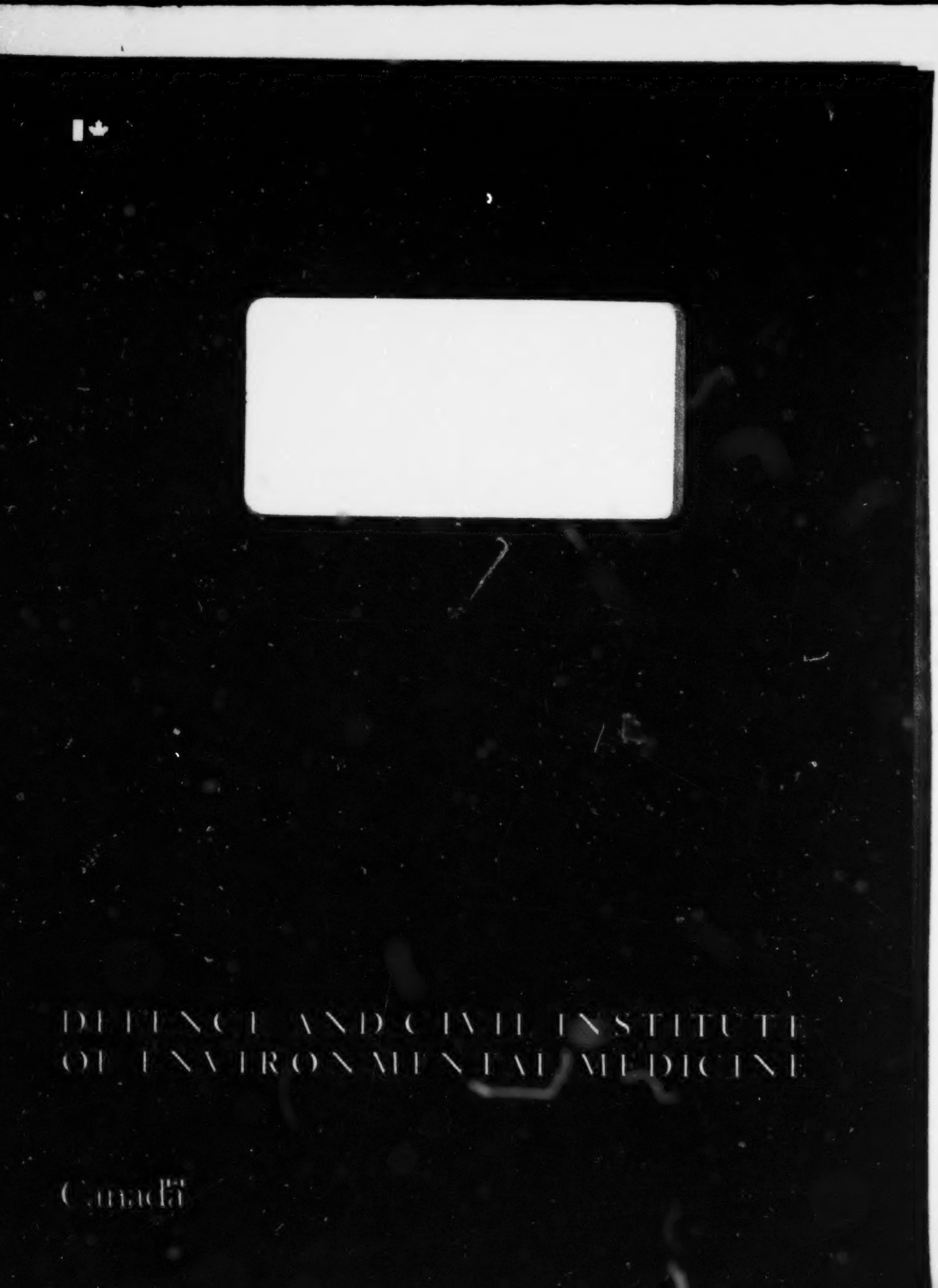
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CREWSTATION ASSESSMENT OF REACH (CAR-III): EVALUATION OF THE MODEL FOR USE IN THE CF AIRCREW/COCKPIT COMPATIBILITY EVALUATION (ACCE)

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ABSTRACT

DCIEM has been tasked by the Directorate of Air Requirements (DAR) to investigate the current status of aircrew/cockpit compatibility in the Canadian Forces (CF) and to make recommendations regarding aircrew selection standards. The use of computer man-modelling has been proposed as the method to address the aircrew/cockpit compatibility evaluation (ACCE). The computer program Crewstation Assessment of Reach (CAR-III), which addresses the issues of reach, vision and head clearance through the construction of operator and crew station models, was considered for that purpose. In this report, the features of the program structure, its input requirements and the accommodation analysis output are reviewed. In addition, a summary of CAR-III's limitations with respect to the operator and crew station models, the program-user interface and complexity of analyses is provided. It is concluded that CAR-III's key limitations are: a) lack of graphics capabilities; b) inability to address the issues of obstruction, ingress and egress; c) elementary derivation of the operator model; d) inadequate representation of the female operator; and e) unknown validity of the reach, vision and head clearance predictions for CF personnel. It is apparent that CAR-III lacks the flexibility and scope of analyses demanded of a primary assessment tool for this tasking. However, it shows promise as a supplementary tool for establishing aircrew selection standards and aircraft design criteria. It is recommended that the validity of CAR's predictions be investigated using a sample from the Canadian population.

1. INTRODUCTION

DCIEM is presently addressing the issue of aircrew/cockpit compatibility (ACCE) in order to identify aircrew selection standards that best reflect the physical requirements of current and future Canadian Forces (CF) cockpits [1,2]. Of primary importance are the aircrew's operation of controls (i.e. reach), internal and external vision, ingress and egress, and body clearance. In order to assess these issues adequately, the aircrew population and aircraft configurations must be represented accurately.

In the first phase of the tasking, methods of assessing aircrew/cockpit compatibility were reviewed for their potential use in the ACCE study. The methods were drawn from a review of known aircraft evaluation techniques employed by countries participating in the Air Standardization Coordinating Committee (ASCC), and traditional human engineering methods to assess work spaces. The methods included cockpit fitting trials using live subjects, anthropometric dummies, partial manikins and stick figure manikins, in both real and mock-up aircraft. In addition, methods employed remote from the cockpit (e.g. drawing board manikins, manufacturers' drawings and three-dimensional computer modelling) were examined.

Computer modelling was identified as the preferred method for use on the basis of its capabilities to: model man; model the crew station; analyse reach, clearances and vision in 3 dimensions; and provide interactive graphic display [3]. Therefore, the major recommendation resulting from Phase 1 was that DCIEM acquire an appropriate man-modelling computer aided design (CAD) program to address the ACCE problem.

BOEMAN, BUBBLEMAN, BUFORD, CAR, COMBIMAN, CYBERMAN and SAMMIE are examples of CAD software packages having some of the features required for the ACCE study. At present, DCIEM possesses an operating version of Crewstation Assessment of Reach (CAR-III)†, one of the man-modelling software packages. Given the availability of CAR-III and its relatively inexpensive operating costs, its applicability as an assessment tool for this tasking justified a detailed evaluation.

This report describes the features and limitations of the CAR-III program and outlines the prospective uses of its output in establishing aircrew selection standards that are compatible with CF aircraft. Relevant information was obtained in two ways; (i) examination of available documentation on the use of CAR-II-A, and (ii) extensive use of the options provided in the CAR-III program, using data collected in field trials or provided by the United States Naval Air Development Centre (NADC).

2. DESCRIPTION OF CAR-III

2.1. History

The original CAR program was developed in 1976 by the Boeing Aerospace Corporation for NADC. It was based upon the Computerized Accommodated Percentage Evaluation (CAPE) and BOEMAN computer models and is used as an aircraft design evaluation tool by the United States Navy (USN). Revisions by Analytics Corporation have been incorporated in the CAR-III version which is currently available for use at DCIEM. The complexity of the program and its interface with the user have been further improved in a fourth version of CAR, now available from NADC.

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† Made available by US Naval Air Development Centre (NADC), Warminster, PA

2.2. Program Structure

Written in Fortran, CAR-III is a combination of four program modules. The first two modules allow the definition of an operator sample (e.g. aircrew) and a crew station (e.g. cockpit) respectively. The third module performs accommodation analyses of reach, vision and head clearance, using crew station and operator files that are generated using the first two modules. The objective of the fourth module is to describe reach envelopes.

The selection of a module and its respective program functions follows a menu-driven structure. Keywords are presented as prompts to the user, for data entry or the specification of analysis options. A HELP feature is provided to give the user more detailed descriptions of the input requirements.

Although CAR-III was designed primarily for interactive use, operator and crew station data may be read into the program from formatted (i.e. alpha-numeric) files that are prepared off-line and entered to a file library. Once read into CAR-III, the data may be edited, printed and/or saved as unformatted (i.e. machine language) files for subsequent use in the accommodation analyses. All input and output data are expressed in imperial units.

2.3. Operator Input Requirements

The operator sample is described by gender and the following 12 anthropometric variables:

1. stature;
2. waist height;
3. seated height;
4. seated eye height;
5. seated popliteal height;
6. buttock-knee length;
7. shoulder-elbow length;
8. forearm-hand length;
9. bideltoid breadth;
10. hip breadth;
11. foot length;
12. hand length.

CAR-III accepts the anthropometric data in one of two ways, as determined by the user; i) actual operator measures obtained during field trials, or ii) means, standard deviations, and intercorrelations from which a Monte Carlo simulation process is employed to generate a sample of operators ($n \leq 400$).

2.4. Crew Station Input Requirements

For input to CAR-III, the user must describe the aircraft crew station in terms of an anchor point, design eye point (DEP), line of sight (LOS), seat parameters, harness restraint, control conditions and aircraft canopy clearance [4], each of which is described below.

Anchor Point:

The crew station anchor point is a fixed location to which a specific body part of the operator is to be positioned. Seven anchor points have been defined in the CAR-III program. They are: the seat reference point (SRP); the DEP; the foot anchor points (FAP) when seated and when standing; the hip; and the shoulder points when seated and when standing.

For applications such as the ACCE tasking, where the operator remains seated, only three anchor points apply. They are the SRP, the DEP and the seated FAP. The SRP is defined as the axis of intersection of the seat back and seat pan. The DEP is the location in the cockpit that is considered to be the optimal eye position for the pilot. The FAP is the location in the cockpit to which the operator requires contact of one foot (e.g. rudder pedal).

The SRP is used as the anchor point for all aircraft having no seat adjustment: the DEP or FAP anchor point is applicable only in aircraft having an adjustable seat (i.e. seat track system).

Design Eye Point and Line of Sight:

CAR-III is able to perform two types of vision assessments; external (e.g. over-the-nose), and internal [e.g. to a head-up display (HUD)]. For either vision assessment, the user must provide definitions of the DEP and a line of sight (LOS) angle above or below the horizon. For external vision analyses, the LOS employed is the line that intersects the DEP and the uppermost surface of the instrument panel, thereby describing a plane above which over-the-nose vision is accommodated and below which it is obstructed. For internal vision analyses, the LOS used is the line that intersects the DEP and a critical location on the head-up display, thereby describing a single line of accommodated eye positions (Figure 1).

Seat Parameters:

Specific seat parameters are required by the CAR-III program so as to position the operator in the seat, and to position the seat according to the desired anchor point. The parameters, which must be provided by the user, include the seat pan angle, seat back angle, seat track system and specific loci that describe the seat track system.

The seat pan angle is the acute angle subtended by the horizontal and the top of the seat pan cushion. The seat back angle is the acute angle subtended by the vertical and the outermost surface of the cushion of the seat back. The seat track system is described in one of four ways:

a) a single track having fore-aft adjustability;

b) a single track having up-down adjustability;

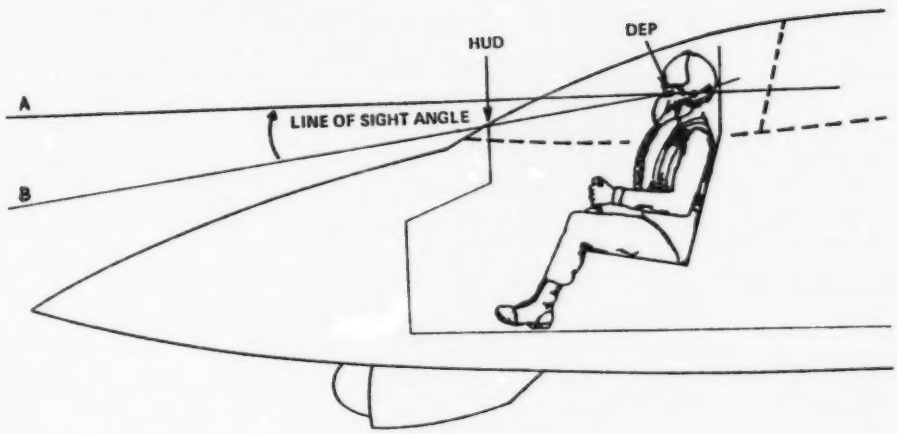
c) a double track having fore-aft and up-down adjustability; and

d) no track (i.e. a fixed seat).

For a), the locations of the SRP in the furthest down-forward (DF) and down-back (DB) positions must be identified. For b), the locations of the SRP in the furthest down-back (DB) and up-back (UB) positions must be identified. The double track system, c), is defined by all three points (i.e. DF, DB, UB) whereas the fixed seat, d), is assumed to have a DB position only (Figure 2).

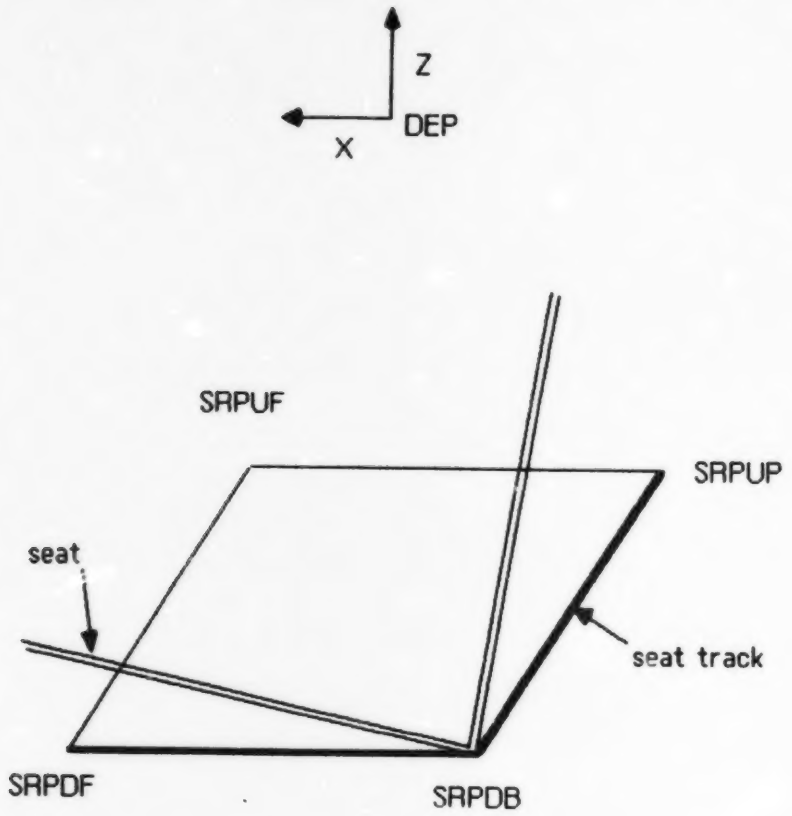
Harness Restraint:

CAR-III models the effect of harness restraint on operator mobility by assuming that freedom of movement varies according to the placement of harness straps over the shoulder. Accordingly, straps that lie closer to the midline of the body are modelled to be less restrictive. In the crew station input file, the user must express the harness position as a percentage of the distance from the midline of the operator to the outer edge of the shoulder.



HUD = *head up display*
DEP = *design eye point*
LOS = *line of sight*
A = *horizontal LOS*
B = *line intersecting DEP and a critical LOS for internal or external vision*

Figure 1. Vision assessment parameters [4].



SRP = *seat reference point*
DEP = *design eye point*
DF = *down-forward*
DB = *down-back*
UF = *up-forward*
UB = *up-back*

Figure 2. The crew station seat track labelling system [4].

Control Conditions:

Up to 50 controls may be identified in defining a crew station. For each control to be reached, the user must identify its appropriate Cartesian (x,y,z) location, related body part, type of grip (if applicable) and harness condition. The importance of each control to the operation of the aircraft must be qualified as "primary" or "secondary." Each of these variables is described as follows:

Location: Control locations are specified relative to a reference point and coordinate system defined by the user. Controls having a range of movement may be represented by two locations that signify the endpoints of that range.

Body Part: The CAR-III program has six options from which the user must choose to perform each reach attempt. They include the left hand, right hand, both hands, left foot, right foot and both feet.

Type of Grip: For hand operated controls, the user must specify the type of grip to be used (i.e. clenched, fingertip or extended). The clenched grip denotes wrapping of the fingers around a control such as a joystick. The fingertip grip represents the grasp required to turn a knob or flick a switch. The extended grip is used to represent fingertip control such as is required to push a button.

Harness Condition: For each hand control, the harness condition (i.e. "locked", "unlocked") determines the appropriate type(s) of reach to be used by CAR-III. There are three types of reach, each defining a zone of operator reach capability that is dictated by the degree of operator restraint:

Zone 1 - Zone 1 reaches are performed with a locked harness and without operator strain. The lumbar, thoracic, intraclavicular and clavicular body segments are immobile while all remaining segments are free to move within their angular limits.

Zone 2 - Zone 2 reaches are less restrictive than those of Zone 1. The harness is locked but the operator strains against it. As a result, mobility of the clavicular body segment is afforded.

Zone 3 - Zone 3 reaches are the least restrictive as they are performed with an unlocked harness. All links are free to move within their angular limits.

Reaches to foot controls are unaffected by the harness condition and, therefore, are all treated as the Zone 3 type.

Primary and Secondary Controls: Since each control identified in the crew station file is flagged as either "primary" or "secondary," separate reach analysis reports are possible for all controls, and primary controls only.

Aircraft Canopy Clearance:

In order to perform an analysis of head clearance accommodation, CAR-III requires the following information from the crew station description file:

a) minimal head clearance distance: the minimum acceptable distance between the top of the seated operator's helmet and the overlying canopy interior;

b) helmet thickness;

c) head clearance location: the point on the canopy assumed to lie directly above the operator's eye.

To test the validity of the crew station input data, the CAR-III program performs checks to assure that the following requirements are met:

a) the coordinate axes must be at right angles to each other;

b) the DF seat location must be in front of the DB seat location;

c) the UB seat location must be above the DB seat location;

d) the UB-DB seat track must be parallel to the Z axis;

e) the UB seat location must be above the DF-DB seat track;

f) the head clearance point must be above and in front of the seat;

g) the FAP must be below and infront of the seat;

h) the seat back angle must be between 0 and 90 degrees;

i) the seat pan angle must be between 0 and 90 degrees;

j) the harness percentage must be between 0 and 100;

k) the LOS angle must be between -90 and +90 degrees; and

l) the helmet thickness must be between 0 and 12 inches.

Collectively, the tests ensure consistency of the crew station description with the assumptions of the reach, vision and head clearance analyses. Error messages are displayed for each inconsistency encountered; corresponding corrections are required prior to conducting an accommodation analysis.

2.5. Accommodation Analysis Options

To perform an accommodation analysis, the user employes the Accommodation Analysis Module. First, the user must identify the appropriate (e.g. unformatted) operator and crew station files to be read into the program. Then, the following limits can be imposed on the analysis.

In any one analysis, all operators, a subset of operators or a single operator from the operator file may be used. This is done in one of two ways; by identifying operators numerically, or by selecting operators according to a desired percentile range for one of the twelve anthropometric input variables (e.g. stature, waist height). Having identified the operator sample, the appropriate clothing condition must be selected from one of three options; nude, summer flight gear or winter flight gear.

Although up to 50 controls can be identified in the crew station file, a maximum of 20 controls can be considered in any one analysis. Therefore, the user must specify, by identification number, a single control or a subset of controls to be used in the accommodation analysis.

There are two reach algorithms programmed in CAR-III. The first algorithm attempts to pass the involved body part (e.g. hand, foot) through the control location. It assumes accommodation if any part of the limb reaches the control point (i.e. the end of the hand or foot need not be placed precisely on the control location). The second algorithm attempts to position the body segments such that the involved body part terminates at the control location. Selection of the appropriate algorithm must be made by the user. An optional output can be requested where, for each control, the identification numbers of the operators who failed the reach attempt are listed.

2.6. Program Execution

Initialization of the Operator File:

Before any accommodation analyses are performed, CAR-III compares the anthropometric input data with the corresponding means of control-group data (i.e. 1964 USN aviator data). An error message is displayed for each operator having a measurement that deviates more than three standard deviations from the control mean. This feature, which allows for the correction of data-entry errors, cannot be overridden during interactive data entry, but can be overridden when data are entered from a file.

Within CAR-III, accepted anthropometric input data are transformed to link segment lengths, according to regression equations derived using data on males. Thirty-one links are constructed to create a man-model that is representative of the human skeletal structure. Seven of the links lie on the midline while twelve are duplicated to represent the left and right sides of the body (Figure 3).

To represent the selected clothing and harness conditions, the operator links are modified in length, position and angular limits of motion. The upper head link is extended by the helmet thickness measurement. The foot link is extended by the thickness of a military boot's heel or sole, for standing or seated operators respectively. To account for clothing on the operator's back, the pelvic, lumbar, thoracic, intraclavicular and clavicular links are moved forward of the seat back. To represent clothing on the legs, the femoral and pelvic links are raised from the seat.

The CAR-III program selects the angular limits of motion from one of nine sets of data, to reflect the interaction of clothing bulkiness (i.e. nude, summer, winter) and the type(s) of reach attempted (i.e. Zone 1, Zone 2, Zone 3). Angular limits of motion for the clavicular links are modified for Zone 2 reaches, to account for the harness location along the shoulder line.

Initialization of the Crew Station File:

For applications where the operator is seated (e.g. the ACCE tasking), the posture of the model must conform to the crew seat. To accomplish this, the CAR-III program employs the seat back and seat pan angles to define the location of the lumbar joint relative to the SRP. The lumbar, thoracic and neck links are then positioned parallel to the seat back. For the purpose of vision, the head links are positioned vertically. An exception is made if the seat back angle dictates a vertical head position which exceeds angular limits of motion. In that case, the head link is placed along the seat back, in line with the neck (Figure 4).

For SRP-anchored crew stations, the operator is placed in the crew seat in the manner described above. Since the SRP anchor is only appropriate when the seat is fixed, there are no further manipulations of the operator or seat before the accommodation analysis is conducted.

For DEP-anchored crew stations, CAR-III is programed to move the SRP, within the range of adjustment of the seat track(s), to optimize the eye position of the operator. Three priorities govern that optimization. The first priority is to position the eye at the DEP. If that is not possible, the objective is to position the eye on the LOS as close to the DEP as possible. If that is not possible, the final attempt is to position the eye as close to the LOS as possible.

For FAP-anchored crew stations, CAR-III is programed to place the heel of the operator at the FAP, without exceeding the tibial angular limits of motion. The FAP anchor is appropriate only for crew stations having a single track seat with fore-aft adjustment.

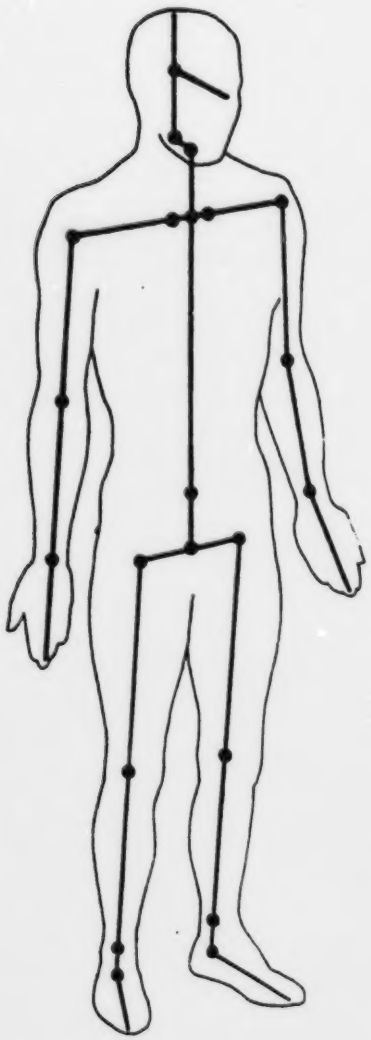
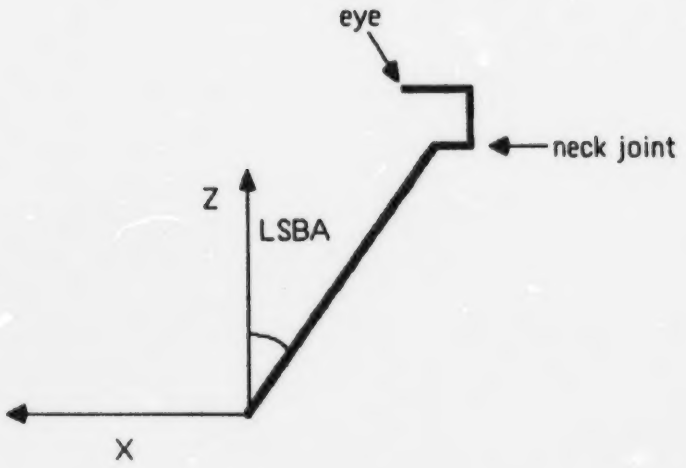
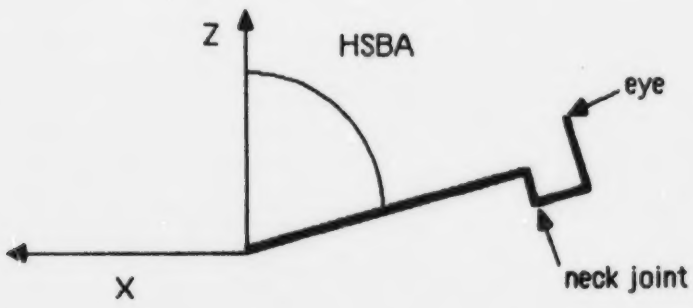


Figure 3. The CAR-III man-model link system [4].



a) operator placement in seat having a low seat back angle (LSBA).



b) operator placement in seat having a high seat back angle (HSBA).

Figure 4. Placement of the operator on the crew station seat [4].

The Analysis:

Once the position of the operator relative to the seat and the anchor point is established CAR-III performs the accommodation analysis. Three components comprise the analysis: reach, vision and head clearance.

Reach attempts are performed to each of the controls specified in the Accommodation Analysis Module. Each reach is simulated by proceeding from the lumbar joint of the operator model and adding successive link lengths in the direction of the control. Where an angular limit would otherwise be exceeded, a link is positioned as close as possible to the direction of the control, without exceeding that limit.

For a reach performed with the hand, links are added in the following order: lumbar, thoracic, intraclavicular, clavicular, humeral, radial and hand. The length used to represent the hand link depends upon the type of grip employed. If the control has a "locked harness" designation, Zone 1 and Zone 2 reaches are attempted. If the control has an "unlocked harness" designation, a Zone 3 reach is attempted.

For a reach performed with the foot, the links employed are the pelvic, femoral and extended tibial-foot. The latter link is defined by the distance from the knee joint to the ball of the foot when the ankle is maximally extended within angular limits.

For a reach that involves either both hands or both feet, a separate reach attempt is performed for the left and right limb. Only the result of the farther reach is reported. Similarly, for a control that has been defined as adjustable, a separate reach attempt is performed to each endpoint of the adjustment range. Again, only the result of the farther reach is reported.

The vision assessment performed in the Accommodation Analysis Module is not under the control of the user. It automatically compares the operator eye position relative to the DEP and LOS, and then summarizes the results for all operators sampled.

The head clearance assessment is optional. It indicates, for each operator, a "pass/fail" performance rating. A "pass" indicates that the distance from the top of the helmet to the canopy clearance point exceeds the minimum head clearance requirement. A "fail" indicates that the head clearance requirement has not been satisfied.

2.7. Accommodation Analysis Output

Each accommodation analysis yields an alphanumeric report summarizing the reach, vision and head clearance results (see example using a foot anchor point in Appendix C). The contents of that report, which are discussed below, are output in the following order:

a) operator sample and crew station descriptions;
b) percentage (of operators) positioned to anchor point;
c) vision accommodation;
d) percentage of crew (operator sample) accommodated; and
e) control summary (reach to each control).

Operator and Crew Station Descriptions:

The report briefly describes the operator sample and crew station used, accompanied by the names of the unformatted files from which the corresponding data were read. The conditions under which the accommodation analysis was performed are also defined (e.g. gender of the operator, type of anchorage, seat parameters, head clearance information, clothing condition and sample size).

Percentage Positioned to Anchor Point:

When either the DEP or FAP is designated as the anchor point, the percentage of operators positioned to that anchor point is stated. Foot-anchored crew station analyses also include the following:

a) the average angle between the seat pan and the tibial link;
b) the percentage of operators seated too far from the FAP, and the average heel-to-FAP distance; and
c) the percentage of operators seated too close to the FAP, and the average heel-to-FAP distance;
d) the percentage of operators that exceeded angular limits of the tibia in order to reach the FAP, and the average heel-to-FAP distance.

When the SRP is designated as the anchor, no statement is made for the percentage of operators accommodated since it is always 100%.

Vision Accommodation:

In the vision accommodation summary, the results are presented in a 3x2 matrix format. The matrix indicates the percentage of operators positioned above/on/below the LOS and forward/behind the DEP. For each combination, the average displacement of the operator's eye from the DEP is recorded. The summary also includes the average horizontal and vertical displacements of the:

a) operator's eye relative to the DEP; and
b) operator's SRP location relative to the SRP-DB location of the seat track(s).

Percentage of Crewpeople Accommodated:

CAR-III prepares a summary of the percentage of the operator sample accommodated for each of the following:

a) vision;
b) head clearance;
c) vision and head clearance;
d) reach;
e) vision and reach;
f) head clearance and reach;
g) vision, head clearance and reach.

Those results are reported separately for "all controls" and "primary controls only," and according to the restraint condition (i.e. Zones 1 and 3 versus Zones 2 and 3).

Control Summary (Reach to Each Control):

In the control summary, accommodation results are listed for each control considered in the analysis. The control name, identification number and location are listed with the associated body part, grip and harness condition.

The results indicate the percentages of accommodated and non-accommodated operators for the type of reach (i.e. Zone) attempted. Of the non-accommodated operators, the average and worst-case resultant displacements of the hand or foot link from

the control location are reported. The x, y and z components of the failure distance are also listed. If desired, the user can specify that the identification numbers of the non-accommodated operators be displayed.

3. LIMITATIONS OF CAR-III

When the objectives of CAR were originally determined by NADC, the program was envisioned as a design evaluation tool for determining the percentage of a population that can be accommodated by a particular crew station design. The cost to run a single accommodation analysis was kept low, so that a design could be perfected through numerous iterations, without undue consideration of expense. It was anticipated that the resulting crew station design could then be analysed using more sophisticated anthropometric models (e.g. COMBIMAN, BOEMAN) before being finalised [4].

In the current study, the CAR-III program was evaluated for its appropriateness to the ACCE tasking. In fairness to the designers of CAR, it must be stated that some of the limitations identified in this report lie outside the original objectives of the program. However, since issues pertinent to the ACCE tasking must be addressed, all relevant limitations that have been identified are listed. To assist the reader, Appendix D contains flow diagrams of each of the CAR program modules.

Again, the information provided here was derived from CAR-II-A documents and extensive use of the CAR-III program. The results are itemized in general categories according to the user interface, the operator model, the crew station model and the complexity of analyses.

3.1. User Interface

1. The HELP feature frequently does not provide additional and/or useful information to program prompts.
2. The nomenclature of the prompt is often inappropriate and confusing. For example, a *generate* function exists within the *generate sample* option, and an *operator sample* file is not distinguished from an *operator measurement input* file.
3. As a result of incomplete menu structures:
   a) within the *generate sample* option of the Operator Sample Module, the save function is provided to update an input file that has been edited. However, if it is selected it corrupts the updated file (see page 28, Appendix C);
   b) within the *actual operator measurements* option of the Operator Sample Module, the calculation of the sample's anthropometric means and standard deviations from raw-data input cannot be executed;
   c) the *high acceleration cockpit (HAC)* option of the Crewstation Module cannot be accessed;
   d) the output of the Reach Envelope Module (i.e. the fourth CAR module) cannot be accessed at all.
4. CAR-III does not allow the user to identify all three coordinate axes. Although the X and Z axes are defined by the user, the Y axis always completes a right hand coordinate system. Therefore, a left hand coordinate system cannot be employed.
5. CAR-III does not adopt a consistent operator numbering system. Operator numbers are redefined each time a new subset is analysed. As a result, the operators identified by number in the accommodation analysis report may not be the same operators identified by corresponding numbers in the operator input file.

6. Crew station controls must always be referred to by their associated identification numbers. Although CAR-III allows the user to identify a subset of controls for assessment, the subset is acceptable only if the control identification numbers run in succession. For example, controls "5-10" can be analysed as a subset but controls "1, 3, 15, 16, and 18" cannot.
7. The output of the CAR-III program's accommodation analysis is not presented in a logical order. A summary of the percentage of operators accommodated for all analyses precedes the results of the individual vision, reach and head clearance analyses. A preferable order of presentation would be the progression from specific to general results.
8. Control names are not printed in full on the accommodation analysis output, and the abbreviated short-form is often not recognizable. This, and the fact that the prompts used to run the CAR-III program are listed in the output, necessitate that the CAR-III user "clean up" hard copies of the analysis prior to formal presentation and/or documentation.
9. The operator sample size is reported as 50 even when fewer numbers are analysed.
10. Identification of an inappropriate file type (e.g. formatted rather than unformatted) causes the current program to abort and/or the data input files to be corrupted.
11. Metric data must be converted to imperial units, by the user, prior to input to the CAR-III program. Similarily, all results are reported in imperial units.
12. The procedure for saving files is inconsistent for the Operator and Crewstation Modules.

3.2. The Operator Sample Model

1. The operator model represents only the bony structures of the human body. It does not consider body segment circumferences to "flesh out" the model. As a result, its representation of the human operator and, therefore, its validity can be questioned for certain applications.
2. Construction of the operator model is dependent on 12 specific anthropometric measurements. As a result, sets of individual or population data that lack the specific measurements are automatically disqualified from all analyses.
3. Transformations of both male and female anthropometric data to link-segment lengths are based on male proportions. Therefore, models of female operators may not be valid.
4. Operator measurements generated by a Monte Carlo process, on occasion, result in negative or zero link segment lengths. This is an example of a self-generated error within CAR-III.
5. The error message indicating that file-input anthropometric values lie outside ± 3 standard deviations of the control-group (i.e. US Naval aviator) mean, does not identify the erroneous variable(s).
6. The selection of a single anthropometric variable in the "measurement percentile option" is redundant. All percentile equivalents, for each operator, are displayed so as to allow the user to decide what operators are to be included.

3.3. The Crew Station Model

1. The crew station model is described only by the seat, a single location on the aircraft canopy and a series of isolated controls. An envelope of the cockpit interior (e.g. instrument panels, floor, canopy contour, seat dimensions) is not provided and, therefore, regions of obstruction are not defined.

2. CAR-III is not programed to be able to position an operator to a FAP when using a double track seat system.
3. Labelling of the input SRP reference points (i.e. DF, DB, UB) is inconsistent for the different types of seat tracks defined. This inconsistency occurs when the angle of an up-down track lies outside a critical angle with respect to the vertical plane. For example, CAR-III sometimes accepts only DB and DF SRP locations for single-track seats (Figure 5). However, if a second track is added to the system the DB location is renamed the UB location, and the DF location becomes the DB location (Figure 6).

3.4. Complexity of Analyses

General:

1. The issues of ingress and egress are not addressed by CAR-III.
2. CAR-III does not possess graphics capabilities to enable visual examination of the analyses, or graphical presentation of results.
3. Details regarding the precise influences of specific anchors, vision targets and head clearance points on the accommodation analysis are not documented. Therefore, the accuracy of the analysis with respect to selection of those variables is not known.

Reach:

1. Simultaneous reaches to two or more controls cannot be analysed.
2. Although 50 controls may be identified in the crew station input file, only 20 controls may be included in any single accommodation analysis.
3. CAR-III is incapable of identifying obstructions to the path of the operator's reach (i.e. the body of the operator, other crew members or cockpit structures).
4. In foot-anchored crew stations, reaches cannot be performed with the unanchored foot.
5. The two reach algorithms (i.e. terminate at control, reach through the control) often yield conflicting accommodation results. The validity of each algorithm is unknown.
6. The harness location along the shoulder line, expressed as a percent, is a highly subjective measure. Its inclusion in the reach algorithm introduces risk of error in the analysis.

Vision:

1. Any one analysis is only appropriate for one attitude of the aircraft. To represent a change in the pitch of the aircraft, the LOS angle must be modified accordingly.
2. The analysis of vision inside the crew station is extremely limited. CAR-III can only determine if the operator's eye is located on a line that intersects both the DEP and the visual target. This situation rarely applies in aircraft. The HUD, for instance, has a cone-shaped area of accommodated eye positions outside which the display cannot be read. Most other displays have wider ranges of unobstructed and, therefore, accommodated vision that cannot be described linearly.
3. The visual accommodation summary (see Appendix C) does not consider operators positioned "at" the DEP.

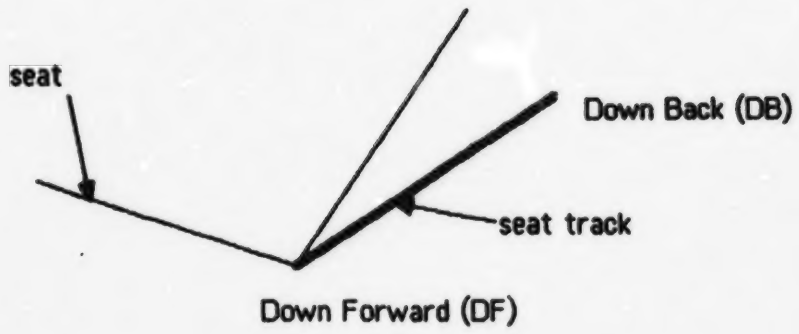


Figure 5. SRP reference locations for single-track seats.

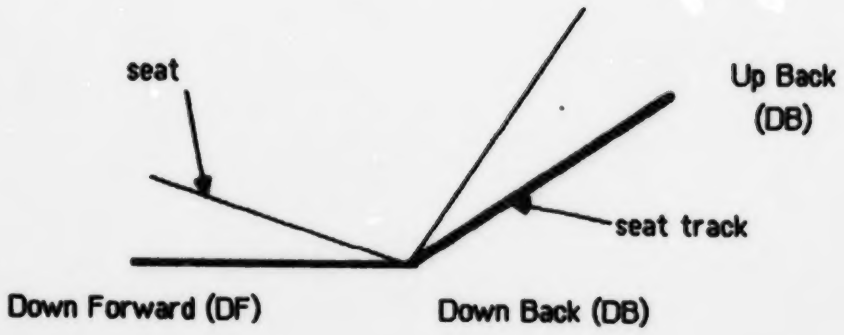


Figure 6. SRP reference locations for double-track seats.

Clearance:

1. CAR-III addresses the issue of head clearance only. It does not consider clearance of body segments with respect to each other, the sides of the cockpit, the instrument panels or the canopy contour.
2. The head clearance location on the canopy interior is taken to be directly above the DEP. As a result, head clearance evaluations of all operators not seated to the DEP are inappropriate, since head clearance is evaluated on the assumption that the operator is successfully positioned with respect to the DEP (Figure 7a).
3. The way in which CAR-III determines head clearance is not clear. It may calculate the resultant displacement between the operator's helmet and the head clearance location, or the vertical distance between those two components (Figure 7b). In any case, neither calculation is appropriate for evaluations where the canopy is curved.
4. Head clearance results for each operator are not included in the accommodation analysis report. Therefore, valuable information such as the average head clearance distance, the worst-case failure distance and the operator identification numbers of those not accommodated, is unavailable to the CAR-III user.

4. ACCE APPLICATIONS OF CAR-III

The potential uses of CAR-III as a tool to address the CF aircrew/cockpit compatibility evaluation (ACCE) are twofold. Pending proof of its validity, CAR-III may be used to evaluate the effects of aircrew selection standards and aircraft design, on reach, vision and head clearance accommodations. These two applications of CAR-III are discussed in the following sub-sections.

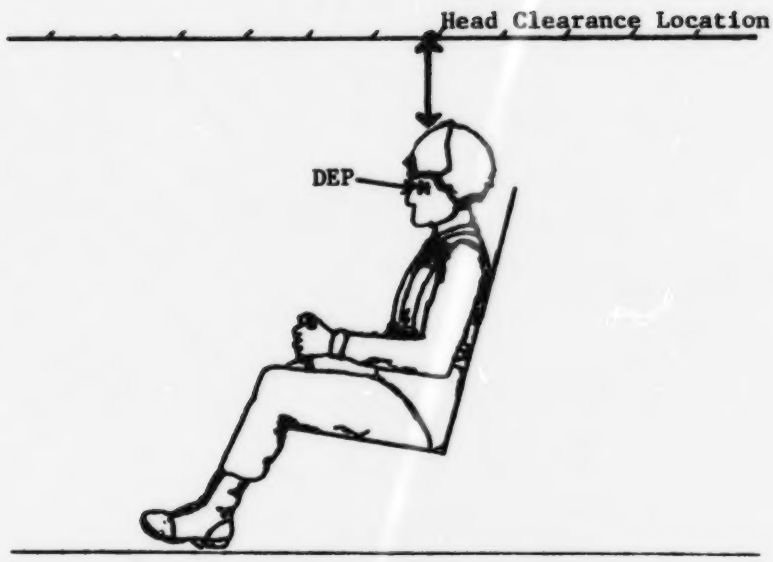
4.1. Aircrew Selection

To examine the relevance of existing CF aircrew (anthropometric) selection standards to physical compatibility with CF aircraft, the CAR-III user may compare the accommodated percentages of; i) a general population, ii) CF personnel, and iii) CF aircrew, for any given aircraft. A progressive rise in the percentages from i) to iii) may indicate an effective screening process. A drop in percentages from ii) to iii), however, may indicate that potentially compatible CF aviators are being rejected. If the percentages of either i) or ii) exceed those of CF aircrew, then it can be concluded that inappropriate anthropometric selection standards are being applied.

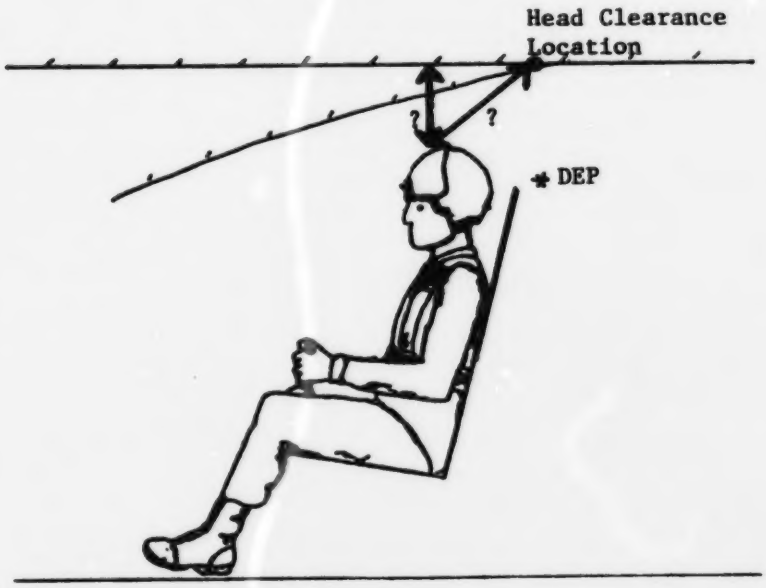
The user may also compare the effects of existing aircrew standards against a proposed or adapted set of standards. For the comparison, a common subject pool would be required from which individuals satisfying each set of standards would be selected. This could be accomplished by using the anthropometric percentile range option of the Operator Sample Module. The size of each operator sample would be indicated by CAR-III, allowing the user to calculate the percentage of the total subject pool that satisfy each set of standards.

Aircrew selection standards that yield a high percentage of physical accommodation may not be feasible when only a small proportion of the population satisfy the selection criteria. Therefore, the percentage of the population satisfying the selection standards and the effectiveness of the standards must both be considered. CAR-III is able to supply information regarding both of these issues.

In future aircrew recruitment procedures, CAR may be used to identify suitable aircraft types (e.g. fighter, helicopter, patrol, transport) or career options (e.g. pilot, navigator) for any given individual. Pending a validation study, this application would require minimal effort on the part of recruitment personnel; the entry of 12 anthropometric



a) assessment with operator eye at the DEP.



b) assessment with operator eye not at the DEP.

Figure 7. Head clearance assessment.

measurements and a pre-prepared crew station file, to the CAR program.

4.2. Aircraft Design

To improve the physical compatibility between aircrew and aircraft, an alternative to modifying aircrew selection criteria is to redesign the cockpit structures. Given a user population (e.g. aircrew), CAR-III is able to predict the reach, vision and head clearance accommodations for any existing or proposed cockpit design. The average and worst case displacements of the operator's hand or foot from a control allow for repositioning of the control to accommodate respectively 50% and 100% of the aircrew sample. The effects of altering various seat parameters (e.g. seat pan angle, seat back angle, seat track system) on reach, vision and head clearance may all be investigated. The optional display of operator identification numbers indicates the individual aircrew members affected by any changes in the design.

5. CONCLUSIONS AND RECOMMENDATIONS

CAR-III produces valuable information regarding reach, vision and head clearance, and provides two particularly useful features. First, CAR-III can be used to simulate the effects of nude, summer and winter clothing conditions, although the accuracy is not known. Most workplace evaluation tools have no such provision. Second, CAR-III provides percentile equivalents of external anthropometric measurements for each operator. This information can be very useful when interpreting the implications of results obtained.

Unfortunately, CAR-III lacks the flexibility and the scope of analyses required of the primary assessment tool for the CF aircrew/cockpit compatibility evaluation (ACCE). This is largely due to its lack of graphical presentations and its inability to address the problems of obstruction, ingress and egress. Furthermore, the simplistic nature of the model (i.e. link man) and its inadequate representation of females raise serious questions regarding its validity in modelling CF aircrew.

On the basis of these conclusions, it is recommended that a validation study of CAR's reach, vision and head clearance predictions be conducted using samples of Canadian males and females. Pending its validation, CAR may be considered useful as a supplementary assessment tool for the ACCE tasking since it is useful to generate populations of various physical proportions and to identify the percentile equivalents of any operator's anthropometric measurements.

REFERENCES

1. 6640-4 (DAR 3-2) 7 Dec 82, Aircrew Anthropometry Tasking.

2. 3600-2 (C) 24 Jan 85, Aircrew Anthropometry Tasking.

3. ROTHWELL, P.L. and R.A. ROOS. Aircrew/Cockpit Compatibility: A Review of Assessment Methods. DCIEM No. 84-R-77, December, 1984.

4. HARRIS, R.M., BENNETT, J. and L. DOW. CAR-II-A Revised Model For Crewstation Assessment of Reach. Analytics Technical Report 1400.06B, Willow Grove, Analytics, 1980.

BIBLIOGRAPHY

BENNETT, J., HARRIS, R. and J.M. STOKES. Crewstation Assessment of Reach (CAR) Validation. Analytics Technical Report 1400.21B, Willow Grove, Analytics, 1982.

Personal communication. E. Gifford (NADC)/D.T. Hickey (DCIEM), 15 June, 1984.

APPENDIX A

CAR-III Accommodation Analysis Output
(Example using Foot Anchor Point)

CREWSTATION ASSESSMENT OF REACH (CAR) MODEL

```
CAR(1-OPER SAMPLE,2-CREWSTATION,3-ACCOM ANALYSIS,4-REACH ENV,5-END)--
ENTER FILENAME FOR CREWSTATION ANALYSIS      --
  INDICATE WHICH CONTROLS ARE TO BE ANALYZED(O=ALL;N,M=RANGE)--
ENTER FILENAME FOR OPERATOR SAMPLE           --
  SAMPLE SIZE(O=ALL;N,M=RANGE)--
  DISPLAY OPERATOR IDS FOR REACH FAILURE(O-NO,1-YES)--
  MEASUREMENT PERCENTILE OPTION (O=NONE,1 TO 12-MEAS NO)--
  CLOTHING(1-NONE;2-SUMMER;3-WINTER)--
  ANALYSIS OPTION(1-ALL OPERATORS,2-OPERATORS ON LOS ONLY)--
  REACH ALGORITHM(1=PASS THROUGH CONTROL,2-TERMINATE AT CONTROL)--
```

CREWSTATION ASSESSMENT OF REACH

SAMPLE:	F18 AIRCREW			FILE:	A.18
OPERATOR NOS:	2- 5				
CLOTHING:	SUMMER				
CREWSTATION:	F18 COCKPIT, anchor = FAP			FILE:	C.18FAP
ANCHORAGE:	FOOT-SEAT			FOOT:	LEFT
FAP:	28.30	10.40	-1.00	LOS ANGLE:	-13.0
DEP:	2.80	0.	33.00	SEAT PAN:	8.5
SEAT BACK:	14.10			HARNESS:	50.%
TRACKS:	DF-DB				
DOWN BACK:	-1.90	0.	5.00		
DOWN FORWARD:	0.	0.	0.	HELMET THICK:	1.3
HEAD CLEARANCE:	1.00				
CLEARANCE POINT:	2.80	0.	42.20		

REACH ALGORITHM: PASS THROUGH CONTROL

FOOT-ANCHOR ACCOMMODATION

% POSITION TO FAP 25.0 MEAN ANGLE 68.3

	%	DIST
TOO FAR FROM FAP	0.	0.
TOO CLOSEATO FAP	75.0	2.4
OUTSIDE ANG LIMITS	0.	0.

VISION ACCOMMODATION

	LINE OF SIGHT ABOVE		ON		BELOW	
	%	DIST	%	DIST	%	DIST
FORWARD OF DEP	0.	0.	0.	0.	0.	0.
BEHIND DEP	100.00	5.31	0.	0.	0.	0.

AVERAGE VERTICAL AND HORIZONTAL DISPLACEMENT FROM DEP

4.20	-3.03

AVERAGE VERTICAL AND HORIZONTAL DISPLACEMENT FROM SEAT DB

-0.09	-0.03

PERCENTAGE OF CREWPEOPLE ACCOMMODATED

POSITION TO VISION POINT	100.00
MIN HEAD CLEARANCE	0.
VISION POINT&MIN HEAD CLEARANCE	0.

	ALL CONTROLS ZONE1&3	ALL CONTROLS ZONE2&3	PRIMARY ONLY ZONE1&3	PRIMARY ONLY ZONE2&3
REACH CONTROLS	0.	0.	0.	0.
VISION POINT&REACH CONTROLS	0.	0.	0.	0.
MIN HEAD CLR&REACH CONTROLS	0.	0.	0.	0.
VISION POINT,MIN HEAD CLR&REACH CONTROLS	0.	0.	0.	0.

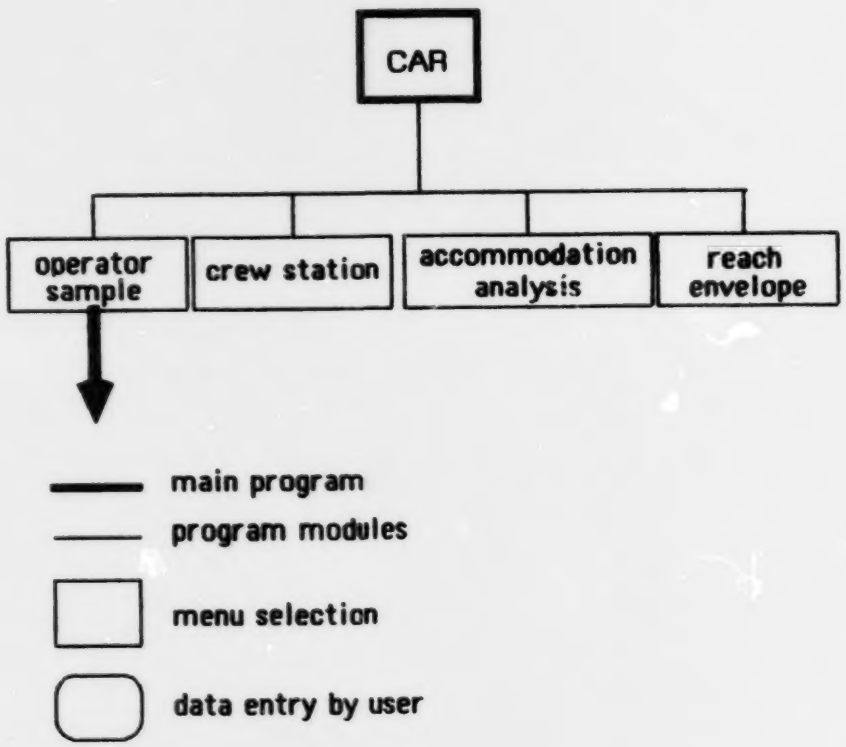
CONTROL SUMMARY

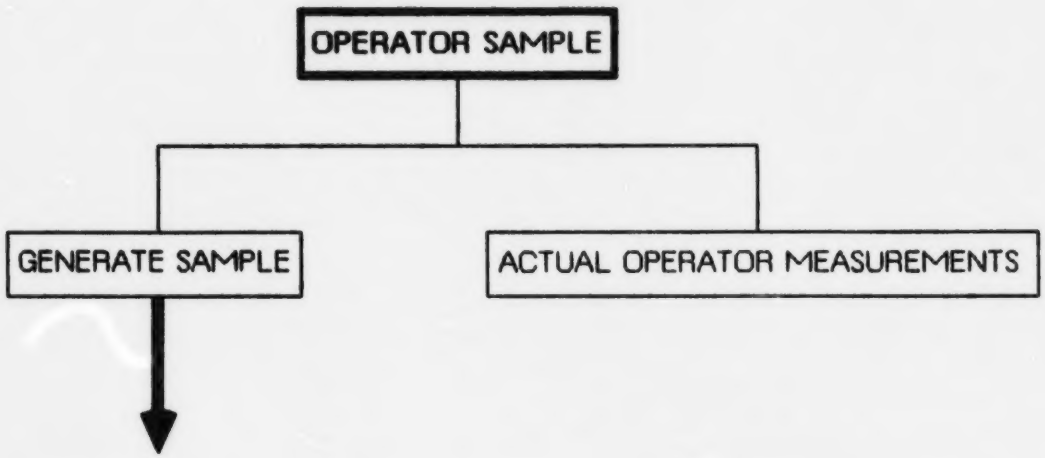
NO	CONTROL NAME	%	HAND FOOT	HARN LOCK	GRIP	LOCATION/ REQUIRED MOVEMENT X	Y	Z	
1	L ST D L		RH	LOCK	CLEN	16.3	3.2	11.5	
	ZONE1 ACCOMODATED	0							
	TOO FAR	100	AVERAGE			-1.3	-1.0	1.1	2.0
			WORSE CASE			-1.8	-1.5	1.5	2.8
	ZONE2 ACCOMODATED	100							
ADJUSTABLE LOCATION						16.1	-2.0	11.1	
	ZONE1 ACCOMODATED	0							
	TOO FAR	100	AVERAGE			-1.3	-1.0	1.1	2.0
			WORSE CASE			-1.8	-1.5	1.5	2.8
	ZONE2 ACCOMODATED	100							

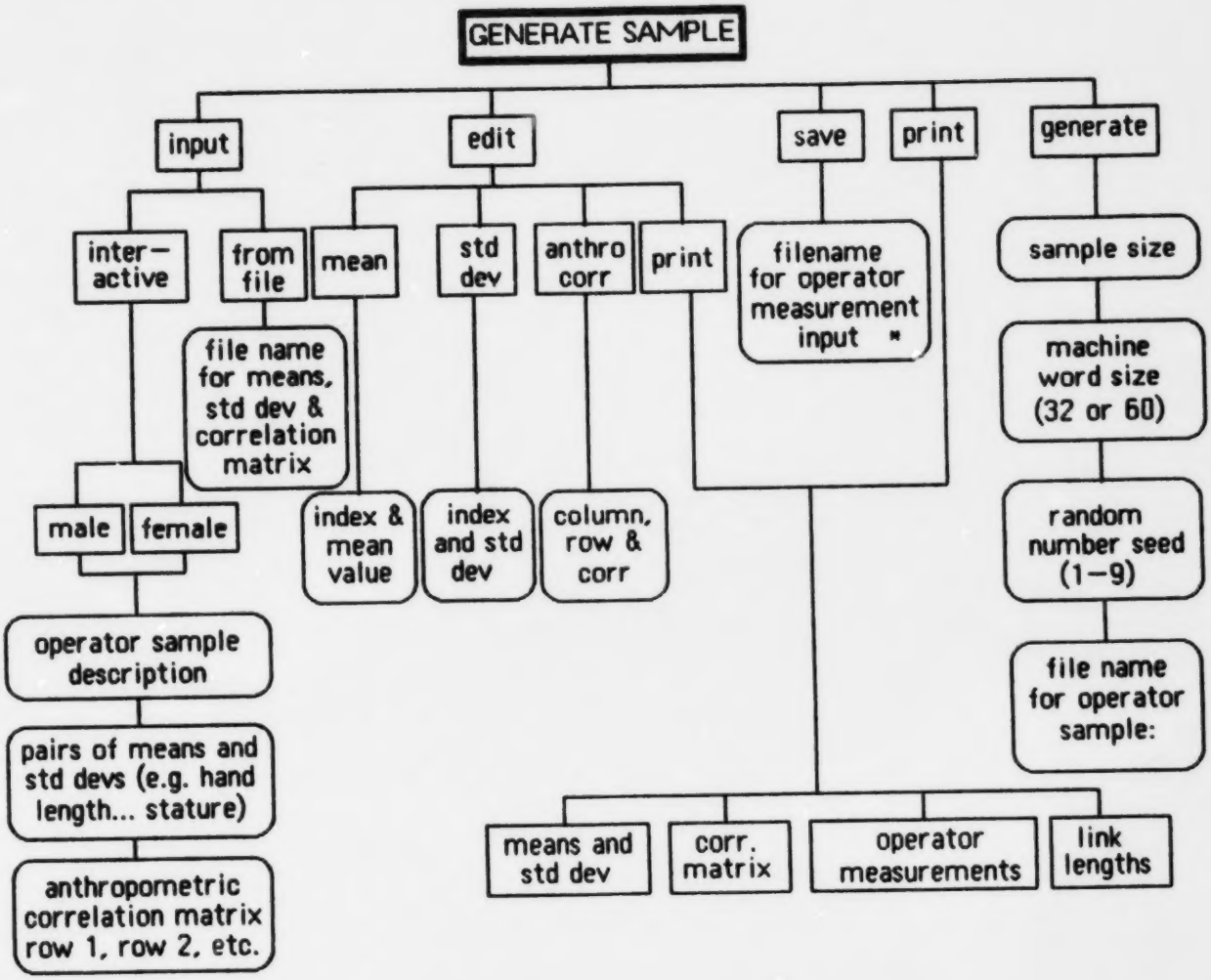
```
BOTH ENDS
     ZONE1 ACCOMODATED      0
           TOO FAR        100
     ZONE2 ACCOMODATED    100
-------------------------------------------------------------------------
 2       LE F      D                LH  LOCK CLEN   15.5   12.4   10.0
     ZONE1 ACCOMODATED      50
           TOO FAR          50   AVERAGE           -0.7   -0.2    0.7    1.0
                                 WORSE CASE        -0.8   -0.2    0.7    1.1
OPER:  3   4
     ZONE2 ACCOMODATED    100

ADJUSTABLE LOCATION                          6.4   12.6    9.1
     ZONE1 ACCOMODATED      50
           TOO FAR          50   AVERAGE           -0.7   -0.2    0.7    1.0
                                 WORSE CASE        -0.8   -0.2    0.7    1.1
OPER:  3   4
     ZONE2 ACCOMODATED    100

BOTH ENDS
     ZONE1 ACCOMODATED      50
           TOO FAR          50
OPER:  3   4
     ZONE2 ACCOMODATED    100
-------------------------------------------------------------------------
 3       G GE                     LH  LOCK CLEN   20.6   13.0   10.7
     ZONE1 ACCOMODATED       0
           TOO FAR          100   AVERAGE           -3.2   -0.8    2.2    4.0
                                 WORSE CASE        -3.8   -1.0    2.6    4.7
     ZONE2 ACCOMODATED       0
           TOO FAR          100   AVERAGE           -1.1   -0.3    0.7    1.3
                                 WORSE CASE        -1.6   -0.5    1.1    2.1
-------------------------------------------------------------------------
 4         JET      JETT         LH  LOCK CLEN   20.3   11.5   17.5
     ZONE1 ACCOMODATED      25
           TOO FAR          75   AVERAGE           -0.4   -0.1    0.2    0.5
                                 WORSE CASE        -0.9   -0.2    0.4    1.0
OPER:  2   3   4
     ZONE2 ACCOMODATED    100
-------------------------------------------------------------------------
 5       P                        RH  LOCK CLEN   14.5  -10.7   11.6
     ZONE1 ACCOMODATED    100
     ZONE2 ACCOMODATED    100
-------------------------------------------------------------------------
 6       G BR                     LH  LOCK CLEN   17.5    9.5    6.6
     ZONE1 ACCOMODATED       0
           TOO FAR          100   AVERAGE           -2.6   -0.3    2.6    3.7
                                 WORSE CASE        -3.1   -0.4    3.1    4.4
     ZONE2 ACCOMODATED      25
           TOO FAR          75   AVERAGE           -0.8   -0.1    0.8    1.1
                                 WORSE CASE        -1.1   -0.2    1.0    1.5
OPER:  3   4   5
-------------------------------------------------------------------------

CAR(1-OPER SAMPLE, 2-CREWSTATION, 3-ACCOM ANALYSIS, 4-REACH ENV, 5-END)--

END OF CAR MODEL
```

APPENDIX B

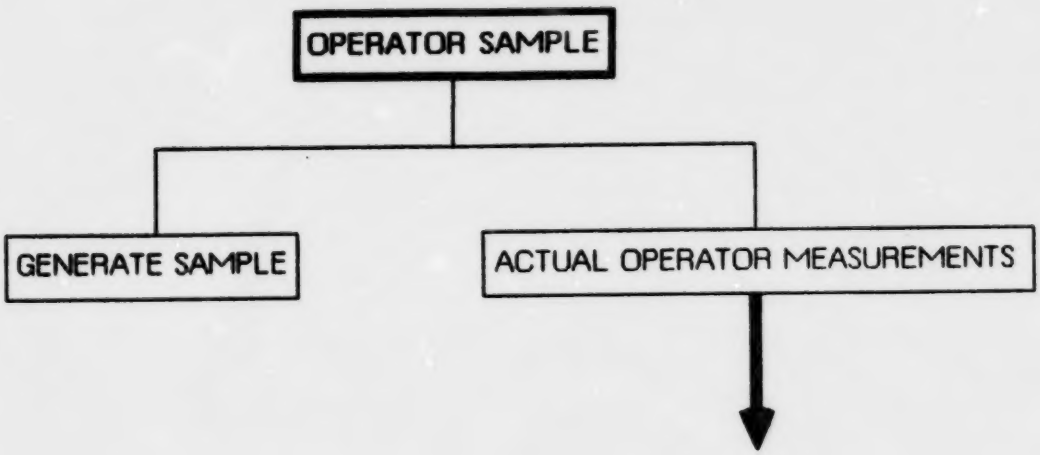
CAR-III Program Module Flow Diagrams

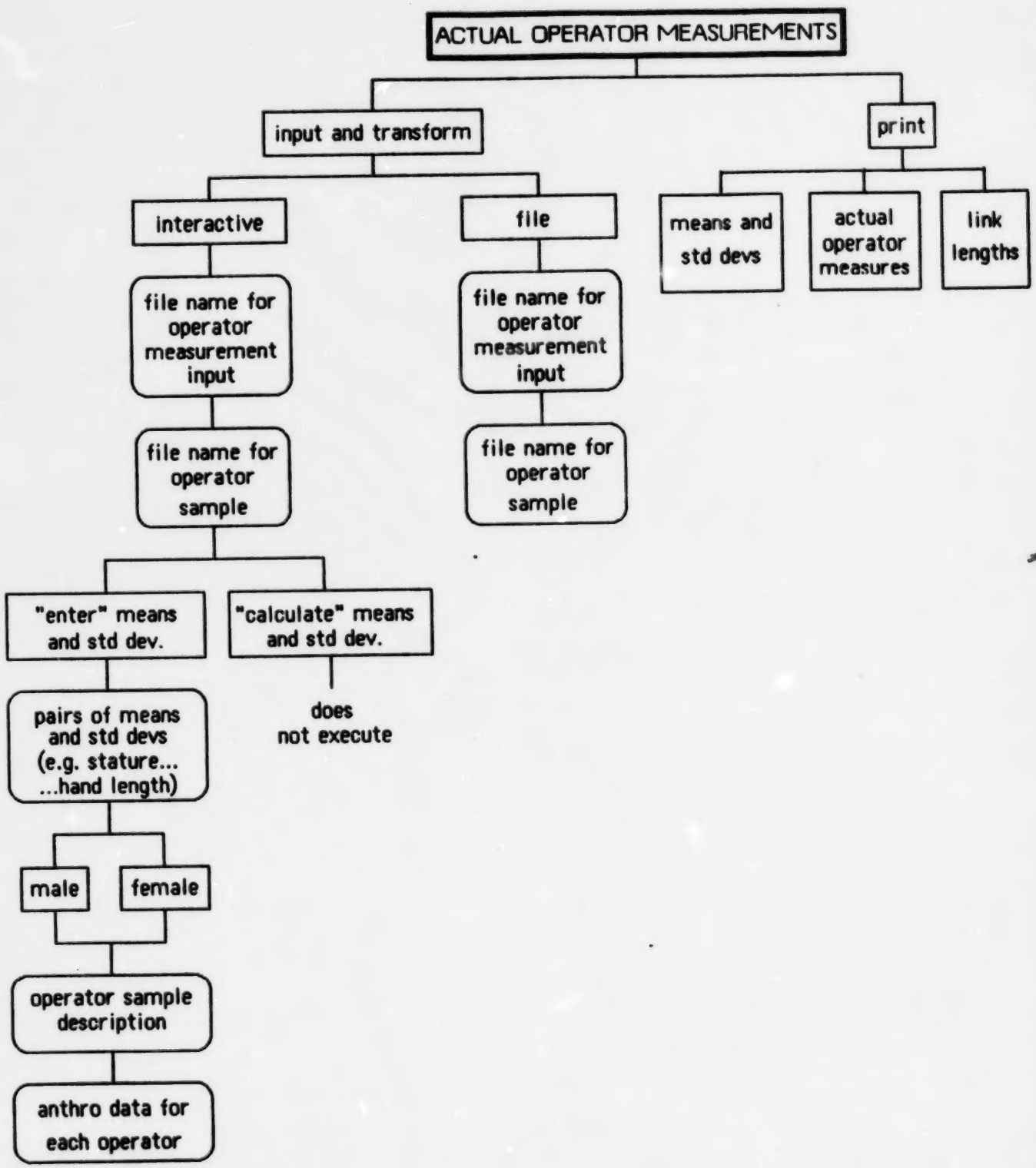

CAR
operator sample
crew station
accommodation analysis
reach envelope
main program
program modules
menu selection
data entry by user

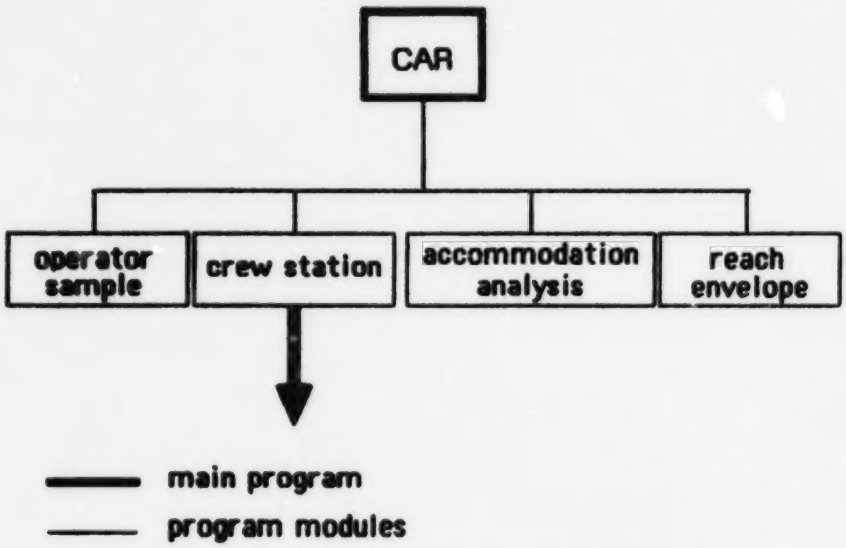

OPERATOR SAMPLE
GENERATE SAMPLE
ACTUAL OPERATOR MEASUREMENTS

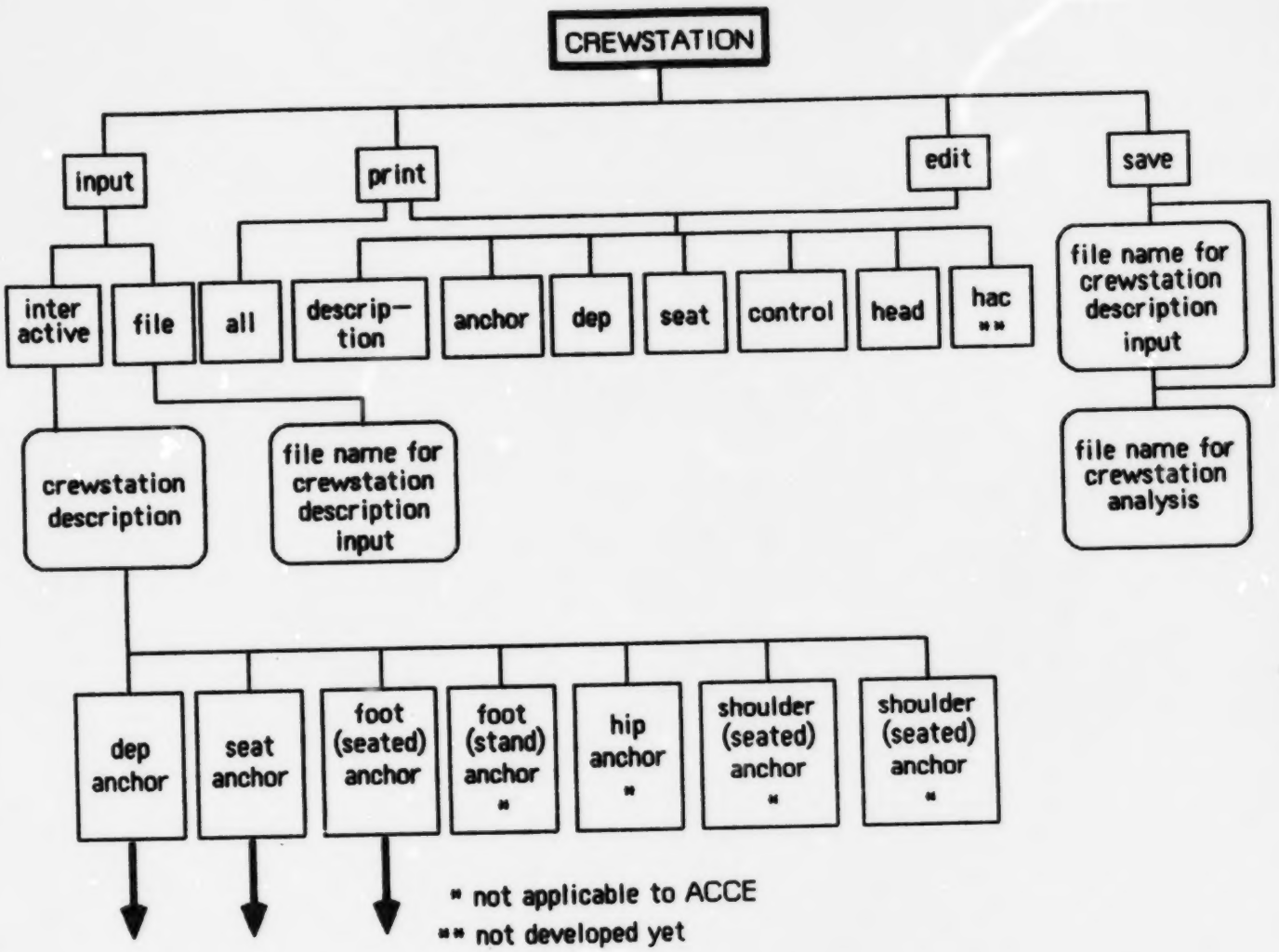


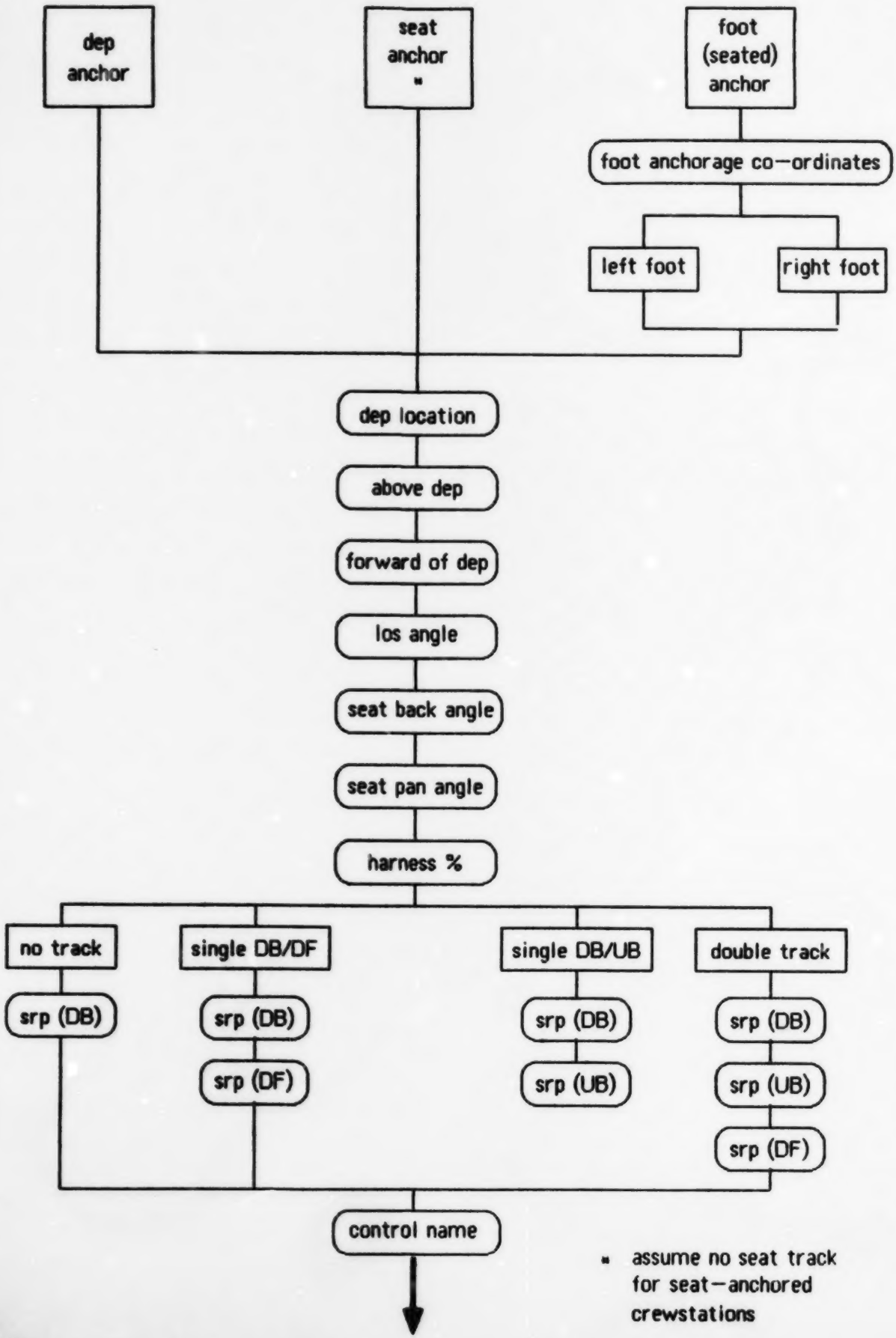
* corruption occurs

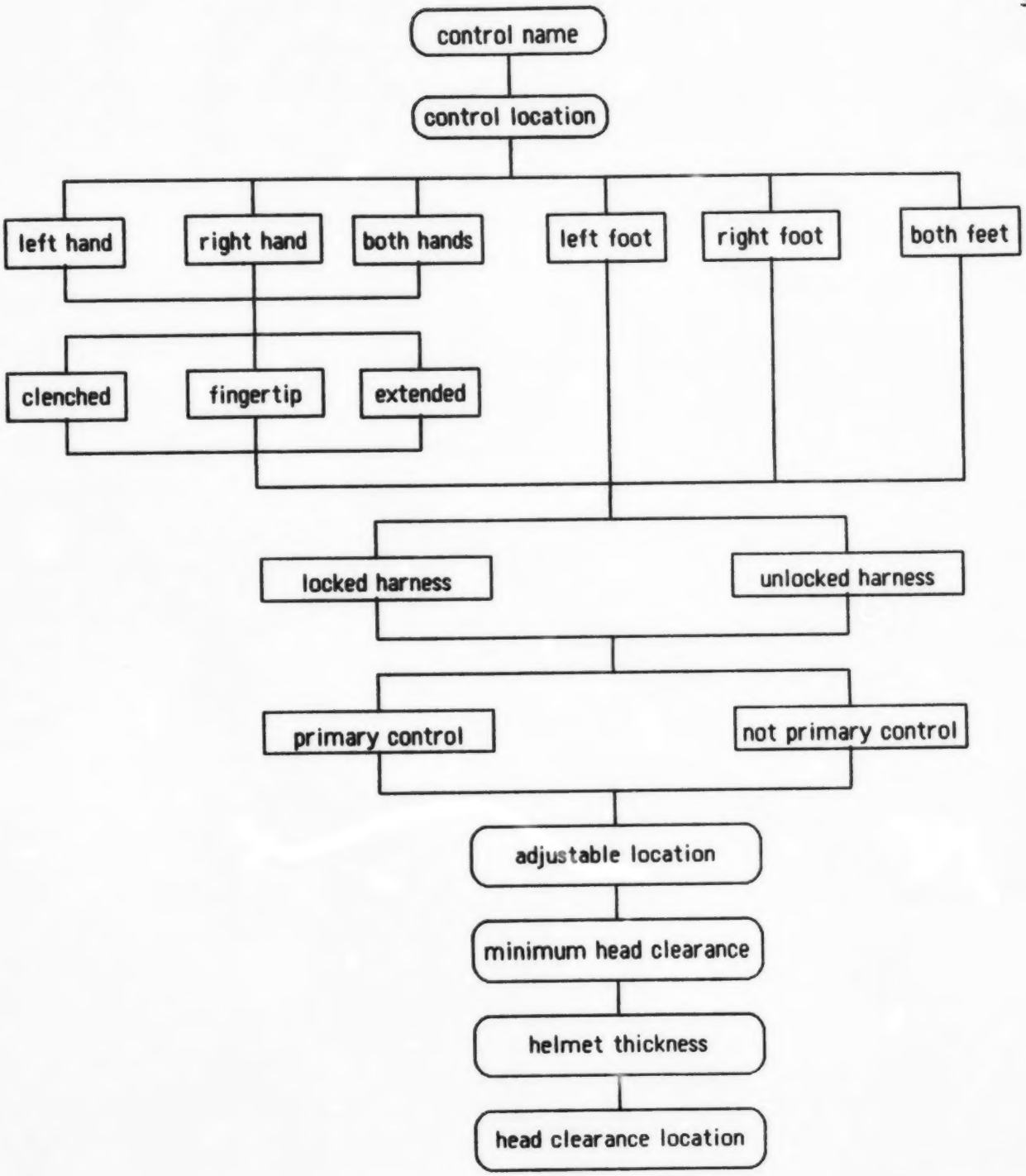

OPERATOR SAMPLE
GENERATE SAMPLE
ACTUAL OPERATOR MEASUREMENTS

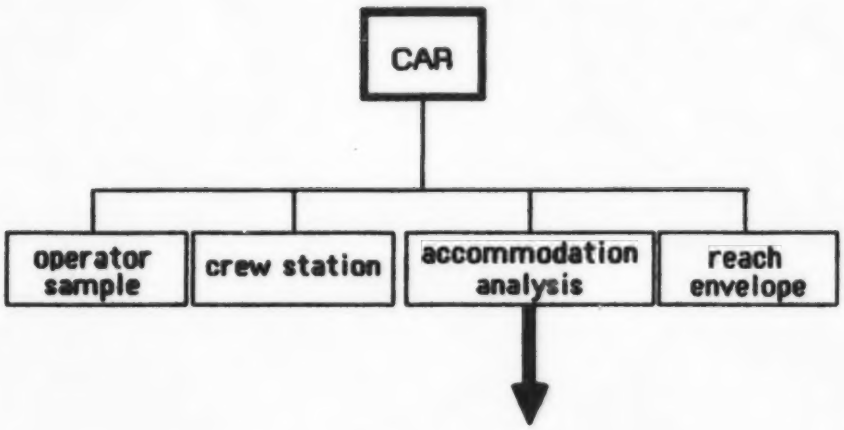

ACTUAL OPERATOR MEASUREMENTS
input and transform
print
interactive
file
means and std devs
actual operator measures
link lengths
file name for operator measurement input
file name for operator measurement input
file name for operator sample
file name for operator sample
"enter" means and std dev.
"calculate" means and std dev.
pairs of means and std devs (e.g. stature... ...hand length)
does not execute
male
female
operator sample description
anthro data for each operator

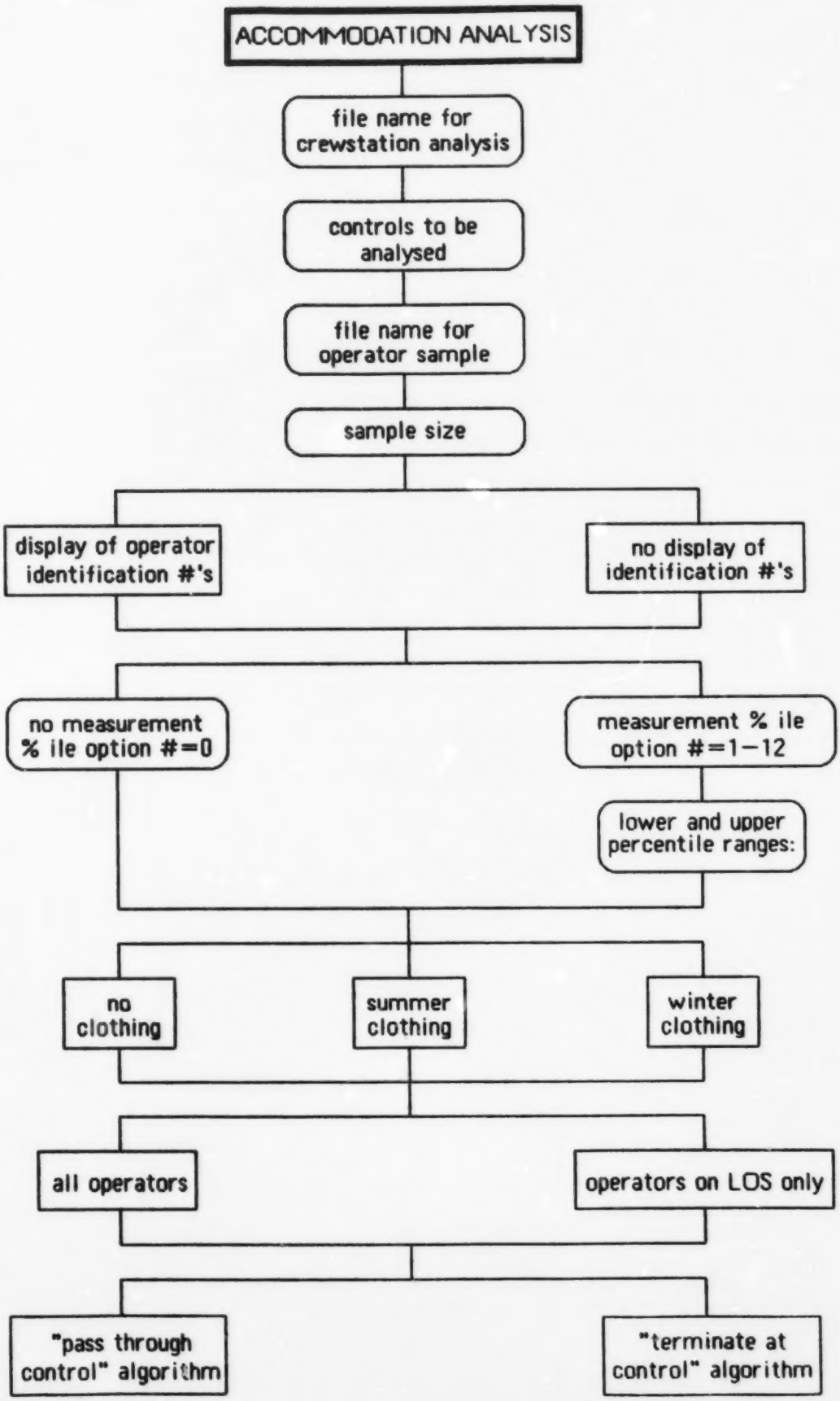

CAR
operator sample
crew station
accommodation analysis
reach envelope
main program
program modules

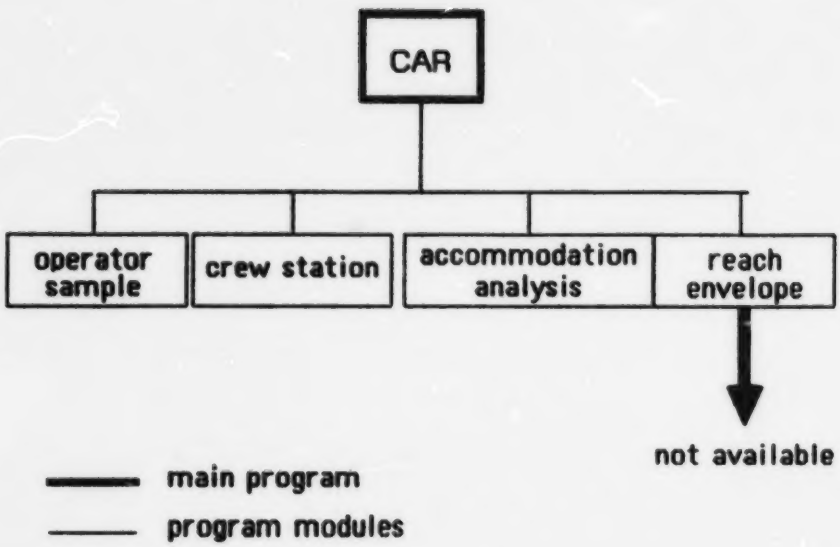

CREWSTATION
input
print
edit
save
inter active
file
all
descrip– tion
anchor
dep
seat
control
head
hac **
file name for crewstation description input
crewstation description
file name for crewstation description input
file name for crewstation analysis
dep anchor
seat anchor
foot (seated) anchor
foot (stand) anchor *
hip anchor *
shoulder (seated) anchor *
shoulder (seated) anchor *
* not applicable to ACCE
** not developed yet


dep anchor
seat anchor *
foot (seated) anchor
foot anchorage co-ordinates
left foot
right foot
dep location
above dep
forward of dep
los angle
seat back angle
seat pan angle
harness %
no track
single DB/DF
single DB/UB
double track
srp (DB)
srp (DB)
srp (DF)
srp (DB)
srp (UB)
srp (DB)
srp (UB)
srp (DF)
control name
* assume no seat track for seat-anchored crewstations


control name
control location
left hand
right hand
both hands
left foot
right foot
both feet
clenched
fingertip
extended
locked harness
unlocked harness
primary control
not primary control
adjustable location
minimum head clearance
helmet thickness
head clearance location


CAR
operator sample
crew station
accommodation analysis
reach envelope
main program
program modules


ACCOMMODATION ANALYSIS
file name for crewstation analysis
controls to be analysed
file name for operator sample
sample size
display of operator identification #'s
no display of identification #'s
no measurement % ile option #=0
measurement % ile option #=1–12
lower and upper percentile ranges:
no clothing
summer clothing
winter clothing
all operators
operators on LOS only
"pass through control" algorithm
"terminate at control" algorithm


CAR
operator sample
crew station
accommodation analysis
reach envelope
not available
main program
program modules